HEART RHYTHM DISORDERS AND PACEMAKERS

Dual-loop circuits in postoperative atrial macro re-entrant tachycardias

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Background: Patients may develop dual-loop re-entrant atrial arrhythmias late after open-heart surgery, and mapping and catheter ablation remain challenging despite computer-assisted mapping techniques.

Objectives: The purpose of the study was to demonstrate the prevalence and characteristics of dual-loop re-entrant arrhythmias, and to define the optimal mapping and ablation strategy.

Methods: 40 consecutive patients (mean (SD) age 52 (12) years) with intra-atrial re-entrant tachycardia (IART) after open-heart surgery (with an incision of the right atrial free wall) were studied. Dual-loop IART was defined as the presence of two simultaneous atrial circuits. After an abrupt tachycardia change during radiofrequency ablation, electrical disconnection of the targeted re-entry isthmus from the remaining circuit was demonstrated by entrainment mapping. Furthermore, the second circuit loop was localised using electroanatomical mapping and/or entrainment mapping.

Results: Dual-loop IART was demonstrated in eight (20%, 5 patients with congenital heart disease, 3 with acquired heart disease) patients. Dual-loop IART included an isthmus-dependant atrial flutter combined with a re-entry related to the atriotomy scar. The diagnosis of dual-loop IART required the comparison of entrainment mapping before and after tachycardia modification. Overall, 35 patients had successful radiofrequency ablation (88%). Success rates were lower in patients with dual-loop IART than in patients without dual-loop IART. Ablation failures in three patients with dual-loop IART were related to the inability to properly transect the second tachycardia isthmus in the right atrial free wall.

Conclusions: Dual-loop IART is relatively common after heart surgery involving a right atriotomy. Abrupt tachycardia change and specific entrainment mapping manoeuvres demonstrate these circuits. Electroanatomical mapping appears to be important to assist catheter ablation of periatriotomy circuits.

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Intra-atrial re-entrant tachycardias (IARTs) are common late after cardiac surgery necessitating an atriotomy—that is, valve replacement or repair of congenital heart disease.[1–6] Multiple IART circuits may develop due to atrial enlargement and fibrosis, as well as incisional scars and other obstacles in the atrial tissue.[5 7–9] Dual-loop, 8-shaped, atrial re-entry was described in humans late after correction of atrial septal defect.[10 11] Dual-loop IART can be recognised when radiofrequency ablation produces a sudden transformation to a new re-entrant tachycardia maintained by the second circuit loop.[10 12 13] Failure to recognise the transformation of tachycardia may preclude radiofrequency ablation of IART.

The aim of our study was to analyse the prevalence and the characteristics of dual-loop IART after cardiac surgery with atriotomy and to define the optimal mapping and ablation strategy.

METHODS

Study population

Consecutive patients admitted to our hospital for radiofrequency ablation of IART late after cardiac surgery involving a right atriotomy were included in the study. Patients who had only atrial cannulation were not included in the study group. Informed consent was obtained from all patients. The procedures followed were in accordance with institutional guidelines.

Electrophysiological study

An 8 F 3.5 mm-tip saline-irrigated radiofrequency electroanatomical mapping/ablation catheter (Navistar Thermocool, Biosense Webster, Diamond Bar, California, USA) or a 7 F 3.5 mm-tip saline-irrigated radiofrequency mapping/ablation catheter (Celsius Thermocool, Biosense Webster) was used for mapping and ablation. One or two additional 6 F quadripolar or decapolar electrode catheters were used as time reference and to further depict right atrial activation pattern. A 5000-unit bolus of heparin was administered intravenously, followed by 1000 units/h. Analysis of tachycardia circuit was based on activation mapping and entrainment mapping according to previous studies.[14 15] The CARTO system (Biosense Webster) was used in 27 of 40 patients (68%) and in 34 of 52 procedures (65%) as described earlier.[8 9] Bipolar voltage mapping was used to identify the areas of scar. Based on previous studies, we used the value of 0.1 mV as cut off value for determination of dense scar.[15 16]

Re-entry circuits

The diagnosis of isthmus-dependent atrial flutter (IDAF) was made by entrainment mapping with post-pacing interval (PPI) $\leqslant$(tachycardia cycle length+20 ms) in the cavo-tricuspid isthmus (CTI). Termination of the tachycardia during ablation of the CTI provided the confirmation for the presence of IDAF. The diagnosis of incisional atrial tachycardia (IAT) was made using the following criteria: (1) there was exclusion of IDAF by entrainment mapping; (2) activation mapping of the right atrium demonstrated sequential atrial activation encompassing >80% of tachycardia cycle length; and (3) entrainment of tachycardia from several sites around the atriotomy scar

Abbreviations: CTI, cavo-tricuspid isthmus; IART, intra-atrial re-entrant tachycardia; IAT, incisional atrial tachycardia; IDAF, isthmus-dependent atrial flutter; PPI, post-pacing interval demonstrated PPIs ⩽(tachycardia cycle length+20 ms). Termination of tachycardia during ablation of isthmus sites provided confirmation for the presence of IAT related to atriotomy scar. The diagnosis of left atrial flutter was made using the following criteria: (1) entrainment mapping failed to show right IART or IDAF; and (2) entrainment of tachycardia from several sites in the left atrium or coronary sinus demonstrated PPIs ⩽(tachycardia cycle length+20 ms). Dual-loop re-entry was considered to exist when (1) radiofrequency ablation of the CTI or radiofrequency ablation of another re-entry isthmus produced sudden transformation of the tachycardia into a different tachycardia, without a pause in between, with some change in intracardiac activation pattern and/or in tachycardia cycle length; (2a) entrainment mapping from a site initially within the re-entry circuit showed a PPI-tachycardia cycle length >20 ms after transformation of the tachycardia or (2b) existence of a distinct second circuit was established by entrainment mapping and/or activation mapping after tachycardia change; and (3) both circuits shared a common isthmus, with two wavefronts merging and forming a common wavefront that propagates between two non-conducting areas (ie, tricuspid annulus and atriotomy scar).

Catheter ablation
Ablation lesions were created with radiofrequency current with a maximum power set at 50–60 W using an EP-Shuttle generator (Stockert GmbH, Freiburg, Germany). Radiofrequency energy was applied in the power controlled mode. Flow rate was initially set at 15–20 ml/min and was modified during current delivery according to catheter temperature. Energy application was continued for a minimum of 30 s and a maximum of 2 min. If tachycardia is stopped, the energy application was continued and the line of lesions across the tachycardia isthmus was completed. Subsequently, conduction block across the tachycardia isthmus was demonstrated.

Outcomes
Acute procedural success was defined as termination of all re-entry circuits during an application of radiofrequency energy, and the inability to re-induce any IART. Programmed atrial stimulation including 1–2 extra stimuli at drive cycle lengths of 600 and 400 ms and burst pacing (minimal cycle length 200 ms) was performed. Further mapping and ablation were performed if a distinct IART was induced. Further mapping and ablation were performed if a distinct IART was induced. A patient was considered having undergone successful treatment if the last radiofrequency ablation procedure within the study period was successful, regardless of whether one or more interventions were necessary. Arrhythmia drugs were discontinued in patients with successful radiofrequency ablation.

Statistics
Statistical analysis was performed using SPSS statistical software V.12.0.1. Data are summarised as mean (SD). Comparisons of means were made using *t* test, comparisons of frequencies were made using Fisher's exact test or χ^2 test as appropriate.

RESULTS
In all, 40 patients were included (22 males) with a mean (SD) age of 52 (12) years. Table 1 depicts the initial diagnosis. Of a total of 61 different IART induced or present at electrophysiological testing, 37 were IDAF, 18 were IAT and 5 were left atrial flutters. In one case, tachycardia terminated during mapping and was not reproducible. In dual-loop IART a mean (SD) of 2.4 (0.7) circuits (range 2–4) were identified compared to 1.3 (0.5) (range 1–3) in single-loop IART ($p<0.001$).

Prevalence and characteristics of dual-loop IART
Dual-loop IART circuits were present in 8 (20%, 4 males, mean (SD) age 53 (12) years, table 2) of 40 patients. In five cases, abrupt tachycardia cycle length change occurred during radiofrequency ablation of the CTI (n = 4) or of a periatriotomy isthmus (n = 1), and dual-loop IART was subsequently demonstrated by the change in activation and/or by the change in entrainment mapping data compared to the data before radiofrequency ablation (fig 1). In one of the five patients, dual-loop IART was suspected from electroanatomical and entrainment mapping data before any ablation and was confirmed by tachycardia change during radiofrequency ablation of the first tachycardia isthmus (fig 2). In three other cases, there was no change in tachycardia cycle length, and changes in activation sequence were seen only retrospectively. Because of apparent failure to alter the tachycardia with radiofrequency ablation, entrainment mapping was repeated and showed that the targeted isthmus was disconnected from the remaining circuit. Additional entrainment mapping revealed that sites around the atriotomy scar were within the remaining circuit. In all cases of dual-loop IART: (1) the common isthmus was situated between the lateral aspect of the tricuspid annulus and a right atrial lateral longitudinal scar; (2) one loop was an IDAF; and (3) the other loop was rotating around a scar or around a line of double potentials in the right atrium free wall, with a lower pivot point between the scar and the inferior vena cava or within the atriotomy scar.

Results of catheter ablation
In all, 52 procedures were performed (1.3 (0.6) per patient); 11 patients required multiple procedures (2–3) because of recurrence of the same circuit, new circuits, primary failure of the first attempt or combinations of the reasons above; 42 procedures (81%) were acutely successful; and, overall, 35 patients had successful radiofrequency ablation (88%). The proportion of patients with successful radiofrequency ablation was lower in the group with dual-loop IART than in the group with single-loop IART (63% vs 94%, p = 0.046).

Catheter ablation of dual-loop IART
In six patients, the CTI was ablated first; in four of them, changes in activation pattern and in tachycardia cycle length were consistent with a change to another circuit, which was confirmed by entrainment mapping and/or activation mapping data. In two patients, there was a change in activation pattern without tachycardia cycle length change. In these two cases, PPIs were identical to tachycardia cycle length at the lateral and medial aspect of CTI prior to radiofrequency ablation, confirming that the cavo-tricuspid was a part of the re-entry circuit and ruling out single-loop circuit within right atrial free wall with bystander activation of the CTI. The absence of change in tachycardia cycle length suggested either that both loops were codominant or that the IART loop was dominant.

In two patients, the lower pivot point of IART circuit was targeted first. In one of the patients, there was a slight (20 ms) change of tachycardia cycle length during creation of a short ablation line connecting the inferior vena cava and the right atrial scar. In the other patient, there was only a change in activation pattern. In both cases, re-mapping demonstrated that the limb around the scar was isolated from a leading circuit around the tricuspid annulus (fig 2).

In dual-loop IART a mean (SD) of 2.1 (0.6) isthmuses per intervention were transected with radiofrequency ablation. In all five patients with successful radiofrequency ablation of dual-loop IART, a short ablation was placed either within the right atrial scar or between the scar and the inferior vena cava. Radiofrequency ablation failed in the first three patients

Table 1 Reason for open-heart surgery in the study group (n = 40)

	Patients (n)
Congenital heart disease	25
Atrial septum defect	11
Endocardial cushion defect	1
Ventricular septum defect	2
Tetralogy of Fallot	6
D-transposition of great arteries	2
Other/complex	3
Acquired heart disease	15
Mitral valve disease	7
Mitral and aortic valve disease	4
Atrial tumor	2
Heart failure (heart transplantation)	2

diagnosed with dual-loop IART. Failures were due to the inability to delineate a critical tachycardia isthmus, because electroanatomical mapping was not available for the patients who had an ECG consistent with typical flutter. Radiofrequency ablation of all circuits was successful in only 63% of patients with dual-loop IART, compared to success rates of 94% in the patients without dual-loop IART (p = 0.046).

Long-term follow-up

The mean (SD) follow-up time was 28 (17) months (range 5–66 months). Of the 35 patients with successful radiofrequency ablation, 1 (3%) patient developed arrhythmia recurrence and declined repeated ablation, 3 (9%) patients developed new arrhythmia which was not further characterised, 3 (9%) patients developed left atrial flutter and 6 (17%) patients developed atrial fibrillation. Overall, 22 (55%) patients remained free of any arrhythmia. There was no significant difference in the percentage of total arrhythmia freedom between patients with single-loop versus dual-loop IART (53% vs 63%, respectively, p = 0.7). However, the outcome according to the type of heart disease tended to be different, with only 40% of patients with acquired heart disease remaining free of arrhythmias versus 64% of patients with congenital heart disease (p = 0.251).

DISCUSSION

Dual-loop re-entry was present in 20% of patients with IART late after open-heart surgery, and was found both in patients with congenital and acquired heart disease, with a similar prevalence. Abrupt tachycardia transformation during radiofrequency application occurred in all cases, but obvious transformation with a change in the cycle length occurred only in five of eight patients. The CTI was involved in all cases and supported one of the circuits, whereas the other circuit was related to the atriotomy scar in the right atrial free wall.

Comparison with earlier studies

Previous observations of dual-loop IART were made in patients late after atrial septal defect surgical closure.[10 11] Our study extends the observation to the population of patients late after heart surgery involving right atriotomy. Dual-loop re-entry is sometimes difficult to recognise and has possibly been overlooked in earlier series of postoperative IART, according to which it appeared uncommon. A complete delineation of dual-loop atrial circuits was first published by Shah *et al*.[10] In a group of patients with IART late after atrial septal defect surgical closure, the prevalence of dual-loop circuits was 33%. A recent study by Magnin-Poull *et al*[11] suggested a prevalence of 70% in a similar population of patients. However, the definition of dual-loop IART in the latest study was based on the analysis of electroanatomical activation maps, and confirmation that the second circuit limb within the right atrial free wall was able to support IART after ablation of CTI was lacking.[12] Indeed, in patients with IDAF who have a conduction barrier in the right atrial free wall, electroanatomical activation maps often suggest the presence of an additional loop around the atriotomy scar. In this situation, it is essential to determine whether the periatriotomy loop is a "functional" circuit that will keep rotating once the first loop is abolished by radiofrequency ablation of the CTI, or whether it is an "innocent" bystander that will not require additional treatment.[12]

Diagnosis of dual-loop circuits

In five patients, dual-loop IART was assumed following an abrupt change in tachycardia cycle length (20–115 ms) during the ablation of the (first) re-entry isthmus. It could be confirmed by entrainment mapping showing that the targeted isthmus was not part of the circuit any more, and that the remaining loop was a different circuit. Change in cycle length occurs when the loop targeted with radiofrequency ablation has

Table 2 Characteristics of the patients with dual-loop macro re-entrant tachycardias, characteristics of the re-entry circuits, and results of catheter ablation

Age (years)	Sex	Diagnosis; main surgical procedure	Double-circuit localisation	CL (ms)	F wave changes*	Isthmus targeted†	Procedural success	Long-term success	Follow-up (months)
65	Female	Anomalous pulmonary venous connection	IDAF and IAT	290/320	Yes	CTI	No	No	58
51	Female	Left atrial myxoma; resection	IDAF and IAT	280/390	Yes	CTI/S-IVC	No	No	50
53	Male	Rheumatic heart disease; aortic and mitral valve replacement	IDAF and IAT	290/290	Yes	CTI/S-IVC/S-S	No	No	27
32	Male	ASD-type sinus venosus; ASD closure	IAT and IDAF	330/330	No	S-IVC/CTI	Yes	Yes	42
62	Female	Tetralogy of Fallot; complete correction	IDAF and IAT	360/475	Yes	CTI/S-IVC	Yes	Yes	30
58	Male	VSD; VSD closure, resection of infundibular pulmonary stenosis	IAT and IDAF	300/320	Yes	S-IVC/CTI	Yes	Yes	11
36	Female	D-TGA; Mustard operation	IDAF and IAT	315/315	No	CTI/S-S	Yes	Yes	6
63	Male	Mitral regurgitation; mitral valve replacement	IDAF and IAT	375/420	Yes	CTI/S-SVC/S-S	Yes	Yes	5

ASD, atrial septum defect; CL, cycle length; CTI, ablation line transsecting the cavo-tricuspid isthmus; D-TGA, transposition of the great arteries; IAT, incisional atrial tachycardia related to a scar in the right atrial free wall; IDAF, isthmus-dependent atrial flutter; S-IVC, ablation line connecting the scar with the inferior vena cava; S-SVC, ablation line connecting the scar with the right superior vena cava; S-S, ablation line connecting a scar to another scar; VSD, ventricular septum defect.
*Changes of flutter waves associated with tachycardia change.
†During mapping termination of tachycardia that was not re-inducible.

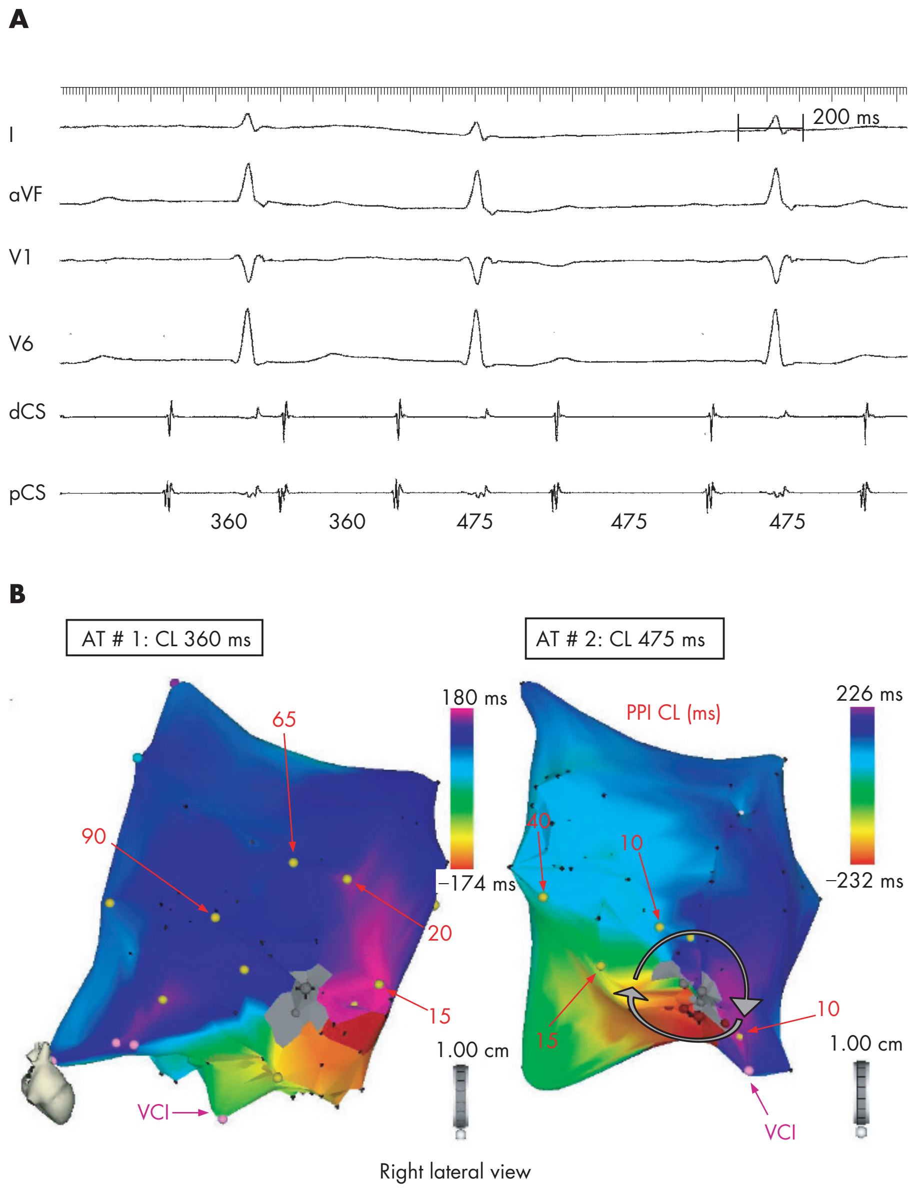

Figure 1 Dual-loop atrial macro re-entrant tachycardia in a 62-year-old patient late after surgical repair of tetralogy of Fallot. (A) From top to bottom: surface ECG leads I, aVF, V1, V6 and bipolar recordings from 4-polar catheter located in the coronary sinus (CS) during radiofrequency ablation of the cavo-tricuspid isthmus (CTI). During radiofrequency current application, a sudden increase in atrial tachycardia from 360 ms (AT#1) to 475 ms (AT#2) is noted with concomitant change in activation mapping (arrows). (B) Left: activation mapping of AT#1 is consistent with counterclockwise, isthmus-dependent atrial flutter, although a clockwise circuit around the lateral scar cannot be ruled out without any additional mapping data. Isthmus-dependent flutter was confirmed by entrainment mapping showing short post-pacing intervals (PPI–tachycardia cycle length (CL) <20 ms) at diverse sites around the tricuspid annulus and very long PPIs in the lateral right atrium, in the region superior and posterior to the atriotomy scar (in grey). Right: activation mapping of AT#2 after the abrupt cycle length change shown in A, suggesting periatriotomy clockwise activation. Entrainment pacing shows that the regions surrounding the atriotomy scar are in the circuit, whereas sites at the CTI are out of the circuit, demonstrating incisional tachycardia related to the lateral atriotomy scar. This second tachycardia terminated during radiofrequency application between the lower aspect of the scar and the inferior vena cava. Abrupt transition of one tachycardia to the other is consistent with a dual-loop tachycardia, with a dominant loop counterclockwise around the tricuspid annulus and a slower loop clockwise around the atriotomy scar.

a shorter revolution time (dominant loop) than the second loop. If both loops have the same revolution time (codominant loops), or if the loop with a longer revolution time is first targeted with ablation, there is no change in cycle length subsequent to the disconnection of the first isthmus. In the three patients with no change in cycle length during radiofrequency ablation, repeated entrainment mapping showed that the targeted tachycardia isthmus had been disconnected from the remaining circuit. In all cases of dual-loop circuits, the PPI–cycle length difference at the first targeted isthmus increased from ⩽20 ms (average 7(5) ms) to >20 ms (average 59 (27) ms) after disconnection of the first loop. Changes in atrial electrogram sequence were seen in all cases and changes in flutter wave morphology were seen in six of eight cases. No changes were seen in two cases, because F waves had a very low amplitude and a long duration (due to diseased and enlarged atria) or because F waves of both tachycardias were similar.

Differential diagnosis
During radiofrequency current application, conduction through the isthmus can suddenly slow leading to a prolongation of the tachycardia cycle length. However, in such situation, entrainment mapping from the isthmus demonstrates that targeted isthmus is still a part of the re-entry.

Radiofrequency ablation of dual-loop circuits
All dual-loop IART had a common isthmus situated between the lateral aspect of the tricuspid anulus and the right atrial lateral longitudinal scar. In general, radiofrequency ablation of two distinct isthmuses seems to be the better option than transection of the common isthmus in the right atrial free wall. First, in patients with atrial enlargement, stabilisation of the ablation catheter is often difficult in this location. Moreover, the longitudinal corridor between the atriotomy scar and the tricuspid anulus is usually broad. Data acquired from high-density anatomical mapping in patients late after closure of an atrial septal defect showed that the mean distance between the line of double potentials and the tricuspid annulus was 4.1 cm.[11] In contrast, the line of radiofrequency lesions to transect an isthmus within the atriotomy scar or between the scar and the inferior or superior vena cava was usually very short.

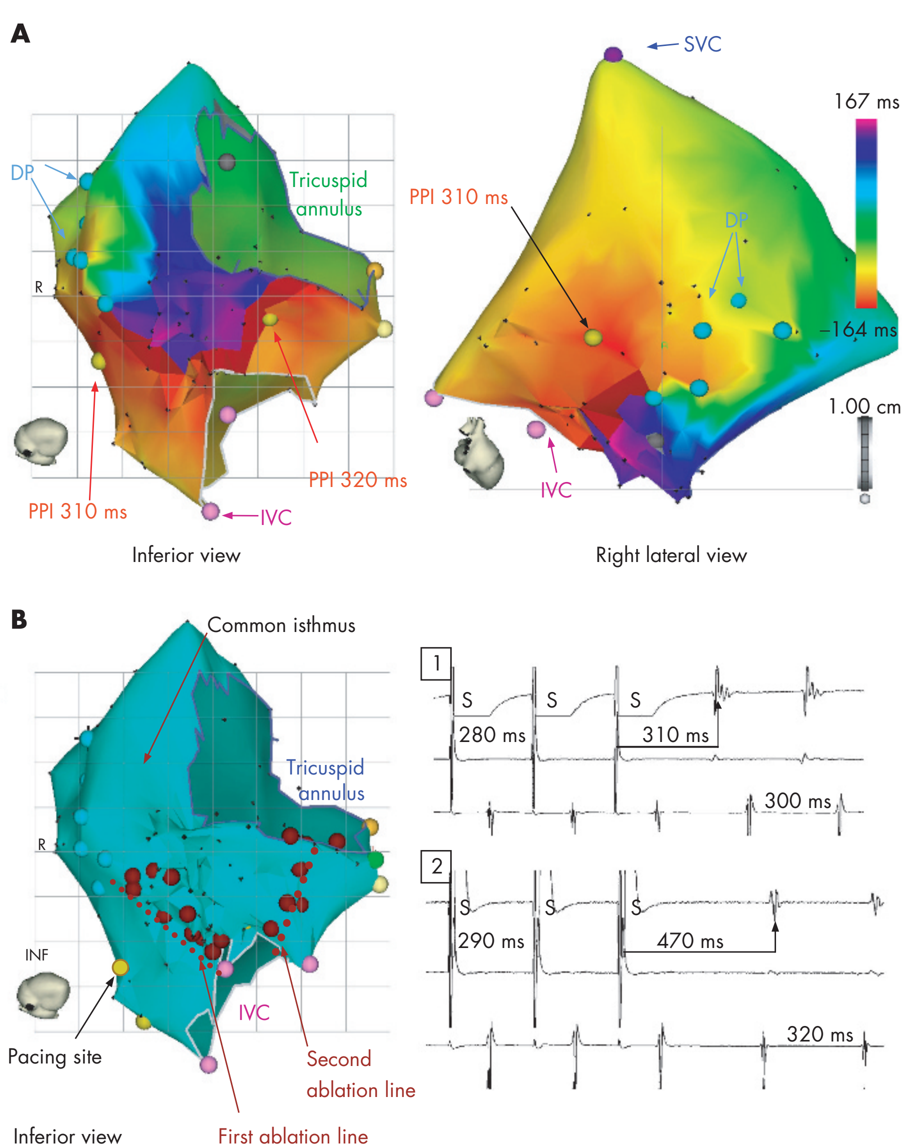

Figure 2 (A) Electroanatomical activation map of the right atrium (inferior and right lateral views) during tachycardia, in a 58-year-old patient late after the repair of ventricular septal defect and the resection of a right ventricular infundibular stenosis. Blue dots represent double potentials (DP). The wavefront descending between a line of double potentials consistent with the atriotomy scar and the tricuspid annulus (common isthmus) separates into one limb pivoting between the line of DP and the inferior vena cava (IVC), and into another wavefront activating the cavo-tricuspid isthmus (CTI) in a counterclockwise direction. Entrainment mapping from sites posterior to the atriotomy scar (short post-pacing interval (PPI) of 310 ms) shows that the area is within the circuit. PPI in the CTI (PPI 320 ms) are slightly longer, but still suggest that the isthmus is part of the re-entry circuit. (B) Left: during the construction of a first line of ablation connecting the line of DPs with the inferior vena cava (red dots, ablation line 1), a sudden 20 ms increase in tachycardia cycle length is observed (not shown). Right: entrainment mapping before (1) and after (2) the first ablation line from a site behind the atriotomy scar (pacing site). After radiofrequency ablation, prolongation of PPI from 310 to 470 ms confirms that the periatriotomy circuit was disconnected from the rest of the re-entry, circulating in a counterclockwise manner around the tricuspid annulus. The common flutter circuit was interrupted by the creation of a second ablation line across the CTI (red dots, ablation line 2). SVC, superior vena cava. INF, inferior view.

Radiofrequency ablation attempts remained unsuccessful in the first three patients with dual-loop IART in this study. The ablation failures were related to the inability to precisely map the periatriotomy region and to delineate a tachycardia isthmus in the first three patients. All the following ablation procedures performed under electroanatomical guidance were successful. This problem is related to our initial strategy to select conventional mapping techniques in patients with ECG showing typical atrial flutter. Electroanatomical mapping was shown to be the best technique to delineate conduction obstacles, atypical atrial re-entry circuits and conduction isthmuses than can be targeted with radiofrequency ablation.[8 9 15]

Follow-up

A relatively large number of patients developed atrial fibrillation or new IART circuits after successful radiofrequency ablation. This may be due to the inclusion of patients with acquired heart disease and particularly with valvular heart disease, who appear at higher risk to develop further tachyarrhythmias than patients with congenital heart disease. Discontinuation of arrhythmic drug after successful radiofrequency ablation may have influenced the subsequent incidence of atrial tachyarrhythmias.

Clinical implications

Patients presenting with IART late after heart surgery involving right atriotomy may have complex re-entrant circuits, and the recognition and characterisation of dual-loop circuits is critical for successful catheter ablation. In clinical practice, electroanatomical activation maps alone do not yield to the diagnosis and entrainment mapping is needed: (1) before ablation, baseline entrainment mapping confirming that the targeted isthmus is in the circuit at both sides of the projected ablation line should be obtained; (2) electrograms should be carefully monitored for any abrupt change in cycle length or activation sequence during each application of radiofrequency energy; (3) in cases of an abrupt tachycardia transformation, or if the ablation fails to terminate the tachycardia, entrainment mapping at both sides of the ablation line should be repeated; and (4) if the PPI increased to a value > cycle length+20 ms, activation mapping or additional entrainment mapping should be performed. Finally, electroanatomical mapping system should be available for all procedures in patients with IART late after open-heart surgery, even when the ECG is consistent with counterclockwise IDAF.

Study limitations

No attempts were made to characterise potential low atrial circuits around the vena cava in association with IDAF. Pericaval circuit in association with IDAF is not clinically relevant since radiofrequency ablation of CTI interrupts both circuits.

During follow-up, there was no attempt to systematically document asymptomatic arrhythmias in the patients who initially presented with symptomatic IART, and asymptomatic IART, atrial fibrillation and other arrhythmia could have been missed. However, this is unlikely since arrhythmia drug treatment was discontinued in all patients with successful ablation.

CONCLUSIONS

In conclusion, dual-loop circuits should be systematically anticipated in patients with IART late after open-heart surgery and should be suspected in case of tachycardia change during radiofrequency ablation. Tachycardia transformation is strongly suggestive of dual-loop IART but hard to notice in some cases. Comparison of entrainment mapping data at critical sites before catheter ablation and after tachycardia change allows us to establish the diagnosis. The circuits delineated so far have a distinctive pattern including an isthmus dependant atrial flutter and a periatriotomy circuit. Electroanatomical mapping appears useful to delineate a tachycardia isthmus of periatriotomy circuits.

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